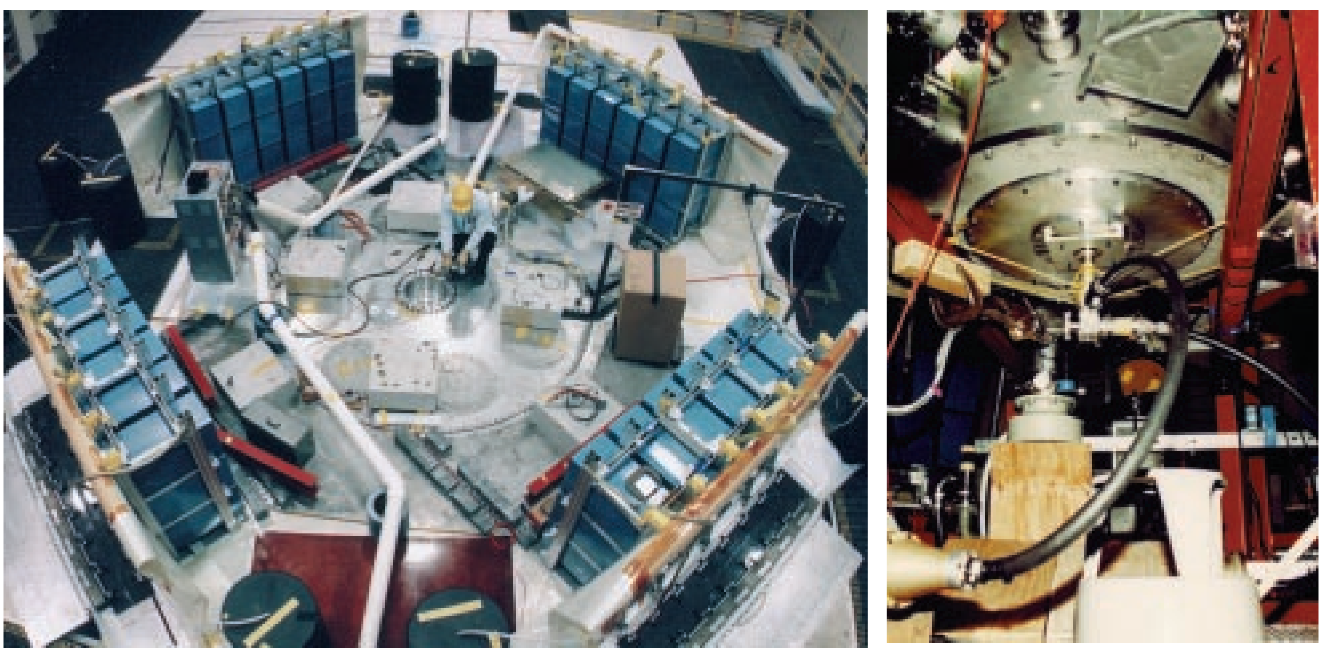
Pulsed-Power Experiments at the Pegasus II Facility

Collaborators from P Division, DX Division, MST Division, X Division, and Bechtel

Overview of the Facility

Pegasus II is a pulsed-power facility at Los Alamos National Laboratory that is used to conduct a variety of experiments in the high-energy-density regime that have applications to the physics of nuclear weapons as well as to basic science. The facility (Fig. II-10) consists of 144 energy-storage capacitors arranged as a two-stage Marx bank with a maximum erect voltage of 100 kV. The 4.3-MJ stored energy for this voltage makes Pegasus II one of the largest capacitor-bank facilities in the world. Pegasus II is used to produce peak currents as high as 12 MA in cylindrical inductive loads and can be operated either with or without a fast opening switch. In addition to conducting plasma- and hydrodynamic-physics experiments, researchers at the Pegasus II facility continue to address technological issues of developing an efficient switch. As a result of the destruction associated with the dissipation of the large stored energy, repair and replacement of components follow each experiment, and shots are fired approximately every two weeks. Several different experimental campaigns in support of the nuclear-weapons program are conducted and involve both heavy, solid liners and thin aluminum foils as the loads for the machine. The foil targets become plasmas during an implosion; in the foil-implosion experiments the imploding plasma stagnates on the axis of the cylindrical system, and the kinetic energy is converted to thermal energy and radiation. The solid-liner experiments are mainly used to address hydrodynamic issues and often involve the impact of the liner on an internal target package. The contact person for Pegasus II projects is Jack Shlachter of P-22.



(a) ***(b)***

Fig. II-10. View of (a) the upper half and (b) close-up of the target chamber in the lower half of Pegasus II.

Summary of Physics Capabilities

Research during the past two years has been focused mainly on hydrodynamic experiments that use a standardized solid drive liner. The active portion of the liner, made from unalloyed (1100 series) aluminum, is a 3.2-g right hollow cylinder (4.8-cm outer diameter, 2-cm height, and 0.4-mm wall thickness) designed to remain at solid-aluminum density during the course of the experiment. For typical Pegasus II operating conditions, the impact of this liner on an internal target with a diameter of a few centimeters results in shock pressures of 100–500 kbar with liner velocities of ~3 km/s at a peak current of 6 MA and an impact time of ~10 μs.

Ejecta Experiments

When a shock wave interacts at a solid/gas (or liquid/gas) interface, some of the solid or liquid material can be emitted into the gas region. These materials can range in size from submicron to hundreds of microns and are referred to as ejecta. The amount, size, and velocity of ejecta will depend on material properties such as the grain size and surface finish as well as the state of the shock wave in the material. This phenomenon occurs in a nuclear weapon when a shock wave interacts at the interfaces between weapon materials and the gases. At this interface, metallic ejecta can be injected into the gas, contributing to the mix of those materials with the gas, which in turn has an effect on the performance of the nuclear device.

In order to characterize and understand ejecta distributions, P Division has developed an in-line Fraunhofer holography technique to make measurements of the ejecta in dynamic systems. The diagnostic has been developed and implemented on numerous experiments based at Pegasus II. The ejecta experiments use the standard aluminum implosion cylinder with various 3.0-cm target packages inside. When the liner driver impacts a target cylinder, a shock wave is set up in the target. The shock wave then propagates through the 400-μm-thick target, and the ejecta are emitted at the target/vacuum interface. An additional 1.6-cm-diameter cylinder (collimator) with various slit openings is used to control the amount of ejecta that passes through to the axial center. The entire load assembly thus consists of three cylinders with the same axis. To make a holographic measurement of the ejecta, a 60-mJ, 100-ps, 1.5-cm-diameter laser pulse is transported along the collimator axis. The laser beam then interacts with the ejecta that have passed through the collimator slits. This interaction occurs some time after the driver-liner cylinder impacts the target cylinder. The actual hologram is made when the scattered light from the ejecta interferes with the unscattered laser light (reference beam) at the plane of the film. Measuring particles of a few microns in size requires that the holographic film be placed a few centimeters from the ejecta. However, at this distance the film would be destroyed in the experiment. To address this problem, our researchers have developed an optical transfer system that relays the interference pattern 93 cm from the ejecta to the holographic film. The hologram contains information about particles ranging from a few microns to a hundred microns in diameter over a volume of 1 cm^3.

In addition to the holography diagnostic, a visible shadowgraphy, dark-field imaging technique has also been developed. Unlike holography, this diagnostic does not provide three-dimensional information; however, it does provide spatially resolved and time-resolved data about the ejecta front as it moves through space. This diagnostic uses a long-pulsed ruby laser (a 450-µs pulse). The laser passes through the ejecta, and a framing camera makes time-dependent, spatially resolved shadowgrams of the ejecta. This technique has been applied successfully to many experiments. Ejecta data have been obtained for both aluminum and tin targets for which the target surface finish and shock strength have been varied.

Complex Hydrodynamic Experiments

Using the same standard aluminum drive cylinder on Pegasus II, our researchers have conducted a separate series of experiments to look at complex hydrodynamic problems. These experiments offer an approach to studying the vorticity and mixing of materials induced by a shock passing across a nonuniform boundary. Although the details of the target design for an individual experiment vary, one example consists of xenon gas surrounded by three layers; the inner and outer layers are made of lucite and the middle layer of gallium (Fig. II-11). The gallium layer is 2 mm thick all the way around, but one half has a smaller radius than the other half. Thus, a step is formed at the junction where these two half-cylinders meet. As the main shock passes across this nonuniform boundary, vorticity and mixing of materials are calculated to occur. We are mainly using axial x-rays to look for the calculated disruptions. Sufficiently high quality x-ray images will provide us with a code benchmark for this particular hydrodynamic phenomenon.

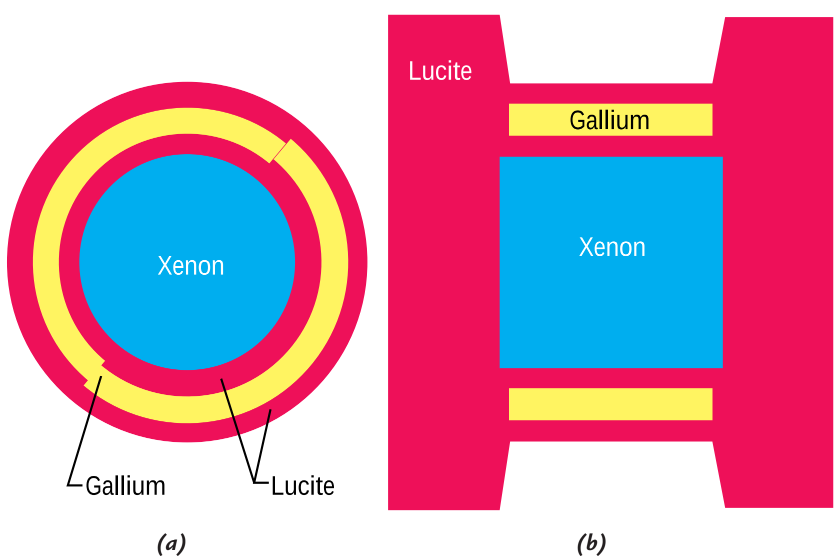


Fig. II-11. Schematic (a) end view and (b) side view of the target package for the complex hydrodynamic experiments.

Liner-Stability Experiments

A series of Pegasus II experiments examining the stability of the imploding liner at near-melt conditions has been conducted. These experiments are motivated by the desire to take full advantage of the Pegasus II facility for performing hydrodynamic studies and to anticipate conditions that will be produced on the Atlas facility that is slated for operation in 1999. Although one-dimensional calculations show that liners can be accelerated to high velocities with a significant fraction of the liner remaining in the solid state, a more detailed analysis using two-dimensional magnetohydrodynamic codes indicates that the liner may break up as a result of instabilities. To provide experimental tests of these calculations, we modify standard liners by coating the inner surface of the aluminum with a thin layer of gold to allow for detailed radial radiographic imaging. For some shots, the liner is fabricated with a precisely machined sinusoidal perturbation in the outer surface. Radiographic images provide experimental data on the observed growth rate of the perturbation as a function of spatial axial wavelength; these data can then be compared with theoretical estimates. Figure II-12 shows radiographic data from a sinusoidally perturbed liner.

Megabar Experiments

The major limitation on imploding-liner conditions is the rise in material temperature associated with the deposition, through the high current, of Ohmic heat. Experiments that require ultrahigh-pressure shock generation, greater than the ~300 kbar achieved with standard aluminum liners on Pegasus II, are of interest for weapons research as well as for basic science. One approach to producing such high pressures on Pegasus II involves the use of composite liners. These systems consist of an outer liner of aluminum with an inner layer of platinum. The aluminum constitutes the bulk of the assembly mass and carries the current. Its low density allows the assembly to achieve maximum velocity. The platinum has a high density and provides for a high shock pressure but remains solid as a result of its high melting point and its relatively low electrical conductivity. With these composite liners, it appears that multimegabar pressures can be achieved on Pegasus II; preliminary results indicate that this approach to high pressures is worth pursuing.

static

6.5-μs exponential-growth regime

8.0-μs nonlinear spike-and-bubble growth

9.5-μs magnetic-field breakthrough

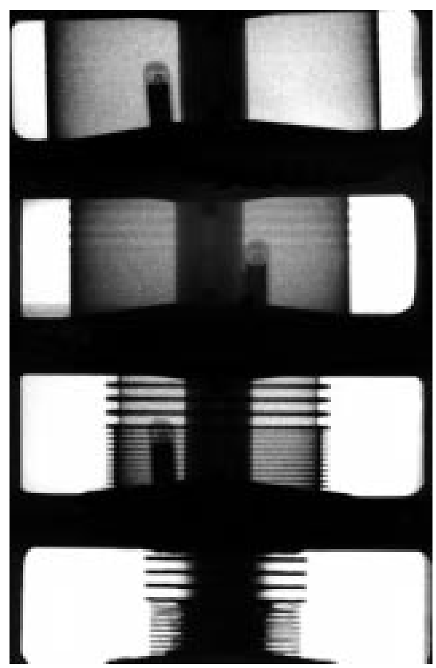


Fig. II-12. Static and sequential x-ray radiographic images of a sinusoidally perturbed liner during implosion.

Near-Term Plans

As the utility of Pegasus II becomes more widely recognized, new experiments and campaigns are being proposed. The present shot schedule includes experiments designed by outside users (from Lawrence Livermore National Laboratory, France, Britain, and Russia) as well as by local researchers. Emphasis for all of these experiments is on issues associated with implosions of heavy metal liners, covering physics topics such as high material strain at high strain rates, Rayleigh-Taylor mix/demix, and laboratory production of ultrahigh magnetic fields. Initial experiments on Pegasus II designed to achieve a peak magnetic field of 6 MG will involve the compression of an axial "seed" magnetic field by the imploding liner. This flux-conservation approach is similar to that used in explosively driven experiments but has the advantages of being fielded in a laboratory environment.

Switch Development

The experiments involving heavy-liner implosions use the Pegasus II facility in a direct-drive mode. Closure of the switches on the capacitor bank couples the current directly to the load through the transmission line. The characteristic waveform for this mode has a peak current at a quarter-cycle time of several microseconds. In the opening-switch mode, the current is allowed to build up to the peak value in a parallel circuit branch and then is rapidly switched to the load. The particular opening switch selected for Pegasus II is a plasma-flow switch; development of this switch is an ongoing activity and involves detailed evaluation of the behavior of a plasma formed between the two conductors in the vacuum coaxial region near the load. Several Pegasus II experiments have been conducted to test the dependence of switch performance on the mass and configuration of the switch material. Additional experiments are being conducted on a smaller pulsed-power facility to analyze possible sources for lost current in the coaxial region. Successful development of opening switches is important for radiation-production experiments on Pegasus II and on its successor, Atlas.

Applications to Basic Science

Pegasus II has applications to a number of important basic-science areas, and the planned Atlas facility will substantially extend these capabilities. The applications extend into the areas of plasma physics, geophysics, planetary physics, astrophysics, and condensed-matter physics. These applications are based upon the capability to produce extreme conditions of pressure, density, magnetic field, and material velocity. As mentioned above, the near-term Pegasus II experiments are designed to reach magnetic fields of 6 MG. When Atlas becomes available in 3 years, axial fields approaching 20 MG should be possible. Field strengths this high can open up new areas of condensed-matter physics. At 2 MG, for example, the Zeeman splitting in materials approaches the thermal energy in a solid and substantially exceeds the magnetic-exchange energy. Thus, magnetic properties of materials should be greatly modified in fields this high. At field strengths above 10 MG, the cyclotron radius of a conduction electron in a crystal becomes less than one lattice constant, meaning that the conventional transport properties of materials are field dominated. Some potential experiments include extending present high-field experimental studies, such as magnetization of high-critical-temperature superconductors and cyclotron resonance in low-mobility materials, and moving into new experimental arenas, such as studying new conductivity mechanisms and quantum-limit phenomena in atoms.

Pegasus II also has the capability to achieve very high pressures, both through shock compression and quasi-adiabatic compressions. With Pegasus II, pressures in the megabar regime are possible. Although such conditions may also be reached using gas guns and diamond anvil cells, the pressures achievable with Atlas will significantly exceed the limits of other conventional techniques. Among problems of great interest in high-pressure research for Pegasus II and Atlas are understanding the thermal properties of the earth's core materials near the center of the earth (i.e., at pressures in the 3-Mbar range) and measuring the equation of state (EOS) of dense, strongly coupled plasmas (which is of importance in testing models of theoretical plasma physics and in benchmarking theories of the interiors of giant planets and brown-dwarf stars). Fundamental studies of material instabilities are also being made at Pegasus II and will be extended on the Atlas facility.

Atlas Capabilities

Atlas is a funded construction project to develop a 36-MJ pulsed-power driver; this energy is approximately 10 times that of Pegasus II. When charged to its full voltage of 240 kV, Atlas will deliver over 40 MA to a load in a pulse rising in about 4 μs. Atlas will provide a rich experimental environment for programmatic experiments in the high-energy-density regime and will be a platform for many basic-physics experiments. Computational studies performed on a 70-g aluminum liner (called the Atlas standard liner) indicate that implosion velocities exceeding 20 km/s will be attained with the inner surface of the liner remaining unmelted. Thus, Atlas will be a premier driver for hydrodynamics and material studies in the very-high-pressure regime. Shock pressures exceeding 30 Mbar will be possible in high-Z materials, and direct, accurate EOS experiments in this range appear feasible. This significantly exceeds the range of any direct EOS experiments conducted by conventional techniques. At these pressures, materials are heated into the multielectronvolt regime and thus will become ionized dense plasmas (e.g., for tungsten at 25 Mbar, the temperature is 8 eV). Atlas will also provide the ability to reach high densities using near-adiabatic compressions. This is important for reaching dense plasma states that cannot be achieved by shock compression. As a hydrodynamic driver, Atlas will be used to extend the high-strain-rate and instability experiments that are now being developed at Pegasus II. Atlas has many uses for basic science. Concepts now being developed for Atlas include dense-plasma properties, materials studies in 20-MG fields, and magnetized target fusion.